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Technical Note

Effect of tempering temperature on microstructure and sliding wear property of laser quenched 4Cr13 steel

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Abstract

4Cr13 martensite stainless steel was quenched by a CO₂ laser and tempered for 2 h at different temperatures in the range 200 °C to 550 °C. The microstructure of treated layer was observed by SEM, XRD and TEM. Tempering leads to the decomposition of a large number of retained austenites in laser quenched surfaces 10 μm thick and the precipitation of chromium carbides which nucleate at phase interfaces, sub-boundaries and within laths. The worn surface and debris formed under various wear conditions were analyzed after a dry sliding wear test. With the increase of normal load or sliding speed, the transition of wear mechanism from mild oxidational wear to severe adhesive wear is observed. For laser quenched 4Cr13 steel, tempering at 350 °C for 2 h leads to the appearance of transition wear effects only at higher loads or faster speeds.

Keywords: Sliding wear; Microstructure; Tempering

1. Introduction

Martensitic stainless steel with a high carbon content has been widely used for wear resistant components in corrosive environments. To improve wear resistance, laser quenching is used to refine the microstructure and increase the microhardness of the treated layer. However, a heterogeneous composition distribution and a large amount of retained austenite are produced on cooling in the treated layer [1–4], so the microstructure of the laser quenched layer or the changes caused by friction heat in the wear process are very important factors in distinguishing the type and the degree of wear. In order to analyze the microstructural transformation mechanism of the laser quenched layer which is caused by friction heat, tempering at different temperatures for 2 h after laser quenching was carried out as described below. The temper stability of laser quenched 4Cr13 steel and its sliding wear property were carefully studied.

2. Experimental procedures

Commercial 4Cr13 steel of composition Fe–13Cr–0.8Mn–0.4Si–0.35C (wt%) was machined into 40×10×20 mm strips and then heated at 1050 °C for 12 min and tempered at 680 °C for 2 h. After these strips were laser-quenched at power 700 W, traverse speed 18 mm s⁻¹ and beam diameter 5 mm, a series of single tracks were cut into the specimens of size 10×4×20 mm. The 10×4 mm plane of specimens was the laser-hardened surface and used as the worn surface after tempering. Different temperatures from 200 to 550 °C were chosen to temper the specimens for 2 h. All wear tests were carried out without lubrication at room temperature using a pin-on-ring friction and wear testing machine. The ring of wear couple was made of WC–8 wt%Co hard alloy with hardness 89 HRA. The wear conditions were: normal load 30–110 N; sliding speed 1.06–1.88 m s⁻¹; sliding distance 264 m.

Foils for transmission electron microscopy (TEM) were prepared using an ion-beam thinning technique. The microstructure of the specimens was analyzed by

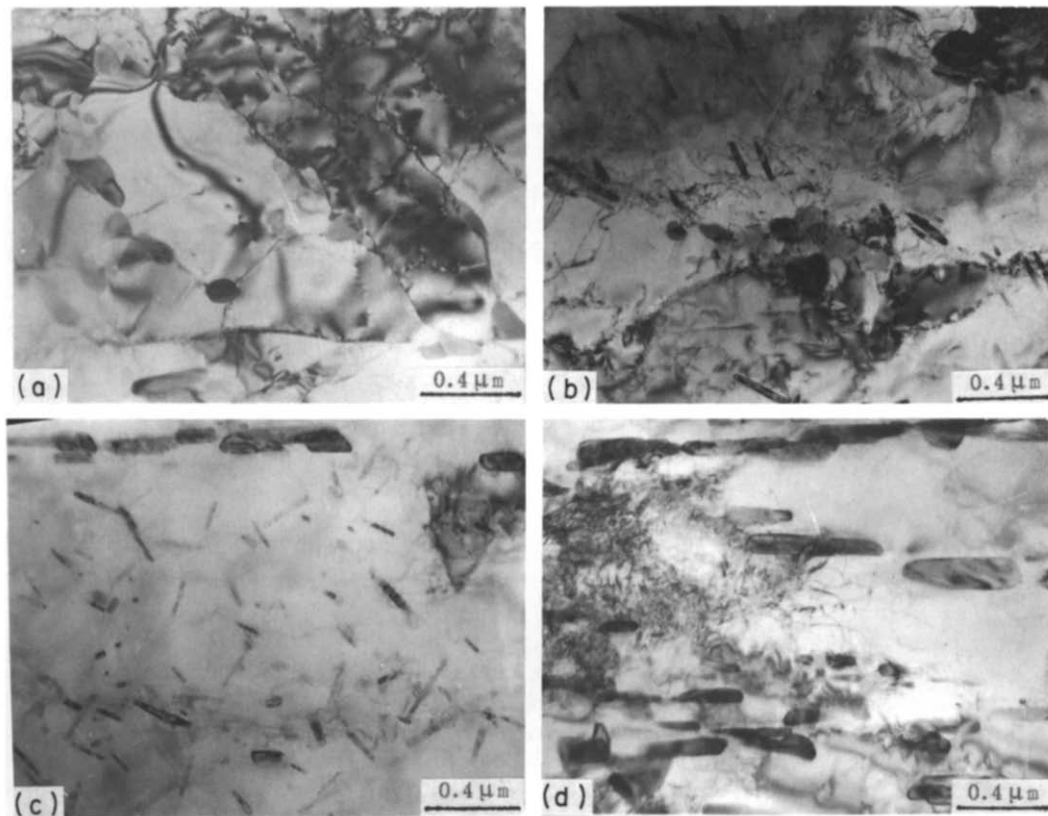


Fig. 1. Morphology of the tempered microstructure of the laser hardened layer at different tempering temperatures: (a) at 200 °C; (b) at 350 °C; (c) at 400 °C; (d) at 550 °C.

a Phillips CM12-type transmission electron microscope. The morphology of the worn surface and debris was examined by a S570-type scanning electron microscope. The retained austenite was identified using a D/max-RB type X-ray diffractometer with Cu $K\alpha$ radiation.

3. Results and discussion

3.1. Microstructure

Fine martensite is obtained in the laser-quenched layer. TEM observation shows that fine martensite consists mainly of a large number of martensite laths with widths in the range 0.1–0.7 μm , but a few with widths up to 1 μm . The coexistence of high density dislocation tangles within laths and local transformation twins is observed in the treated layer.

The morphology of the tempered microstructure of the laser-hardened layer is given in Fig. 1. When tempered for 2 h at 200 °C, the metastable fine martensite in the treated region begins to decompose. The carbon atoms tend to diffuse to sub-boundaries or phase interfaces and fine alloy cementite represented as $(\text{Fe,Cr})_3\text{C}$ gradually nucleate there. The morphology of the precipitates nucleating at the sub-boundaries is shown in Fig. 1(a). These precipitates are very small.

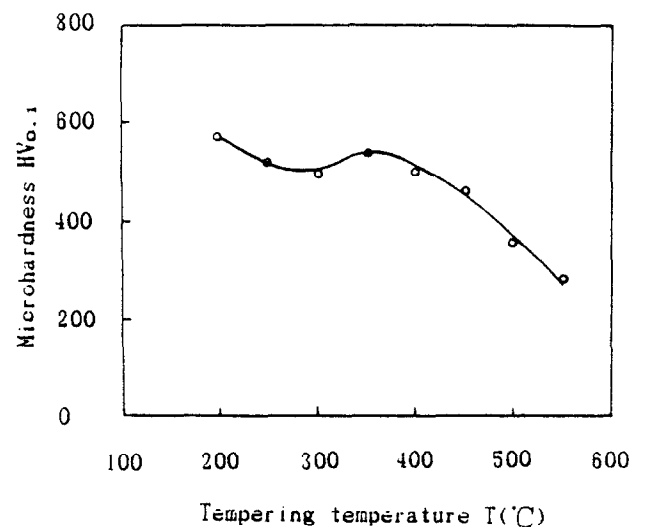


Fig. 2. Relationship between tempering temperature and the microhardness of the laser-quenched layer after tempering.

When tempering is carried out at 350 °C, the diffusion ability of carbide-forming elements increases, and alloy carbide replaces the less stable cementite which dissolves as a finer alloy carbide dispersion forms. A separate nucleation and growth mechanism of alloy carbide appears during tempering. A large amount of rod-like carbide with length 0.15–0.25 μm and diameter 230 Å

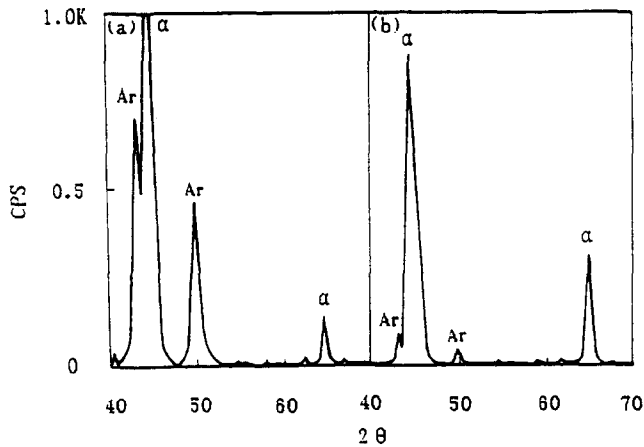


Fig. 3. X-ray diffraction pattern of the laser quenched layer: (a) XRD of the surface layer; (b) XRD of the sub-surface layer after the 10 μm skin has been worn away.

nucleate at the phase interfaces or within the laths, as shown in Fig. 1(b). Some alloy carbide is pinned by the dislocations. As shown in Fig. 2, a mild hardening effect occurs at 350 °C. This is different from conventional tempering treatment. In general, after tempering at 350 °C for 2 h the dislocations in the conventionally quenched microstructure almost completely disappear. Selected electron diffraction analysis shows that these precipitates are alloy carbide Cr_7C_3 . But when laser-quenched 4Cr13 steel was tempered for 2 h at 400 °C, the dislocations disappear and the coexistence of chromium carbides Cr_7C_3 and Cr_{23}C_6 is found in Fig. 1(c). With the increase of tempering temperature to 550 °C,

chromium carbides coarsen and Cr_{23}C_6 carbide continues to precipitate, as shown in Fig. 1(d).

3.2. Decomposition of the retained austenite

The thickness of the laser-quenched layer was about 0.8 mm in the conditions used in this study. Fig. 3 gives XRD results of a laser-quenched surface layer (Fig. 3(a)) and a sub-surface layer after a 10 μm skin was worn off (Fig. 3(b)). Quantitative analyses indicate that the content of retained austenite in the surface layer of the laser-quenched zone is 4.13%, but only 3.6% of retained austenite is measured after the 10 μm surface layer is worn off. It can be concluded that a large amount of retained austenite obtained by laser quenching mainly distributes in the 10 μm surface layer.

Fig. 4 states that the decomposition degree of the retained austenite after tempering for 2 h at different temperature values in the range 200–550 °C. The tempering stability of the retained austenite obtained by laser quenching is higher than that of the retained austenite obtained by conventional quenching methods.

3.3. Wear volume and wear mechanism

The wear volume of specimens tempered 2 h at different temperatures is shown in Fig. 5. From Fig. 5, it can be seen that the wear volume is very small when the load and the speed are low. For example, the wear volume of the specimen is less incremental with the sliding speed under the conditions of 30–50 N in load. However, the wear volume increases rapidly

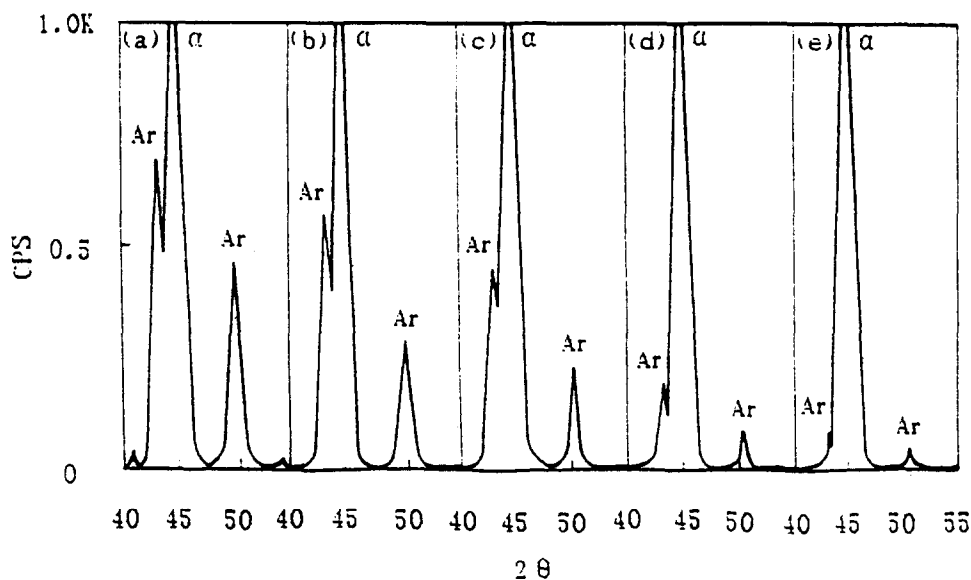


Fig. 4. The decomposition degree of the retained austenite after tempering: (a) laser quenched layer; (b) tempering at 200 °C; (c) at 350 °C; (d) at 400 °C; (e) at 550 °C.

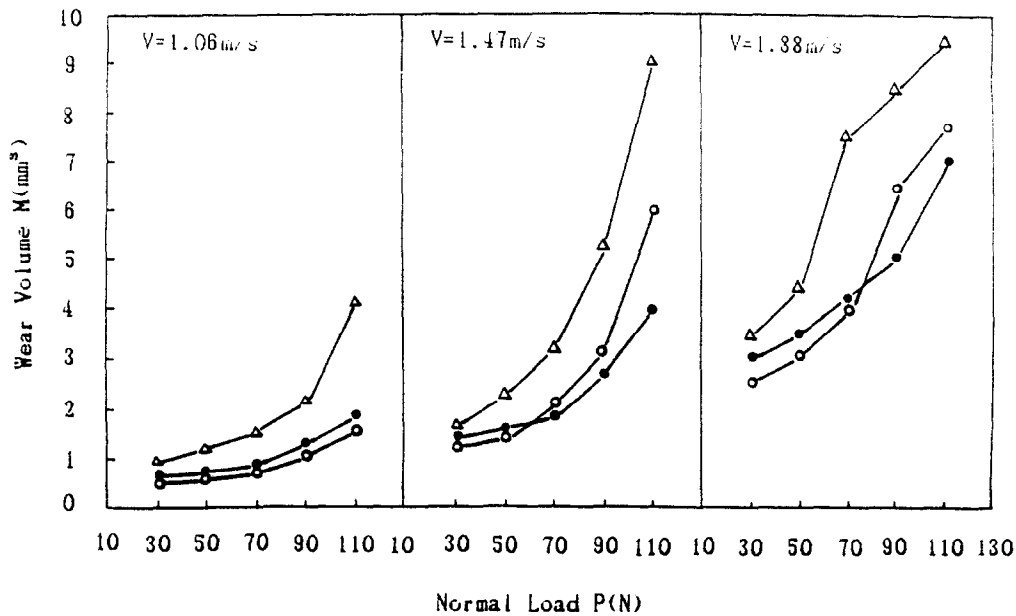


Fig. 5. Wear volume of the specimens tempered for 2 h at different temperatures: Δ at 550 °C; \bullet at 350 °C; \circ at 200 °C.

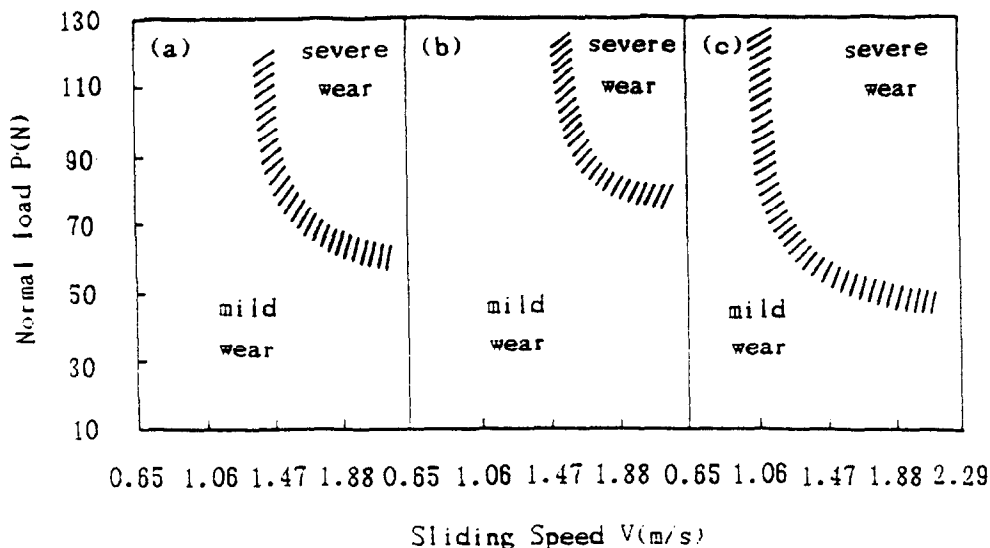


Fig. 6. Diagram of wear mechanism transition from mild wear to severe wear under different tempering conditions: (a) at 200 °C; (b) at 350 °C; (c) at 550 °C.

with loads beyond a certain test load as shown in Fig. 6, a transition of wear degree from mild to severe wear appears with the increases of load and speed. It will be known from the latter analyses that the mild wear is oxidation-dominated wear and severe wear mainly belongs to adhesive wear with delamination. From Fig. 5, it is found that the wear volume of a specimen tempered for 2 h at 350 °C is almost equal to that of specimens tempered for 2 h at 200 °C, but distinctly less than that of specimens tempered for 2 h at 550 °C.

The above experimental results show that the change in testing conditions could cause the transition of the

wear mechanism. The dry sliding wear process of 4Cr13 steel consists of mild wear with oxidation features and severe adhesive wear with plastic deformation and scale-like features.

From Fig. 6, tempering at 350 °C for 2 h could lead to the appearance of the transition wear effects only at higher loads and higher speeds because of the fine rod-like carbide pinned by the dislocations. With the further increase of tempering temperature, coarsening of carbides and a decrease in the microhardness of the treated layer lead to a rapid wear and its transition wear effects occur earlier than those of specimens tempered for 2 h at 350 °C.

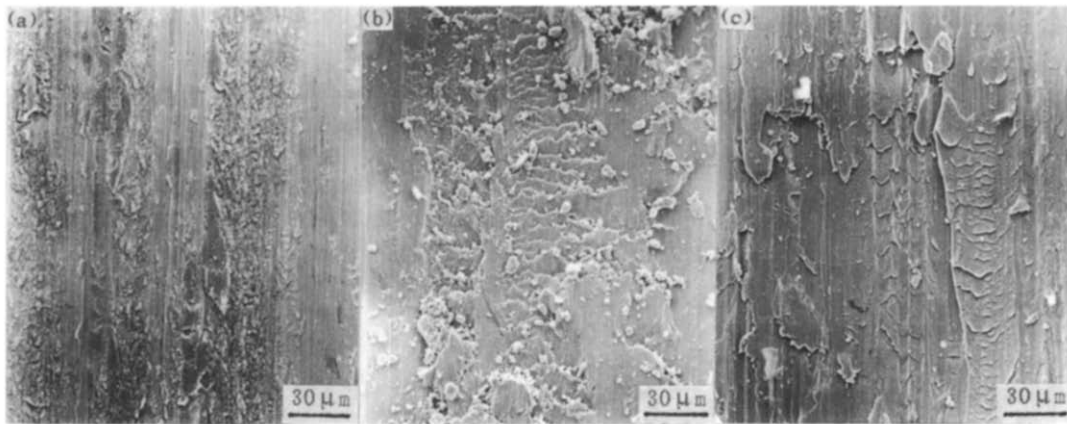


Fig. 7. Scanning electron micrographs of the worn surface of the pin specimens tempered for 2 h at 550 °C: (a) $P=30$ N, $V=1.06$ m s⁻¹; (b) $P=70$ N, $V=1.47$ m s⁻¹; (c) $P=90$ N, $V=1.88$ m s⁻¹.

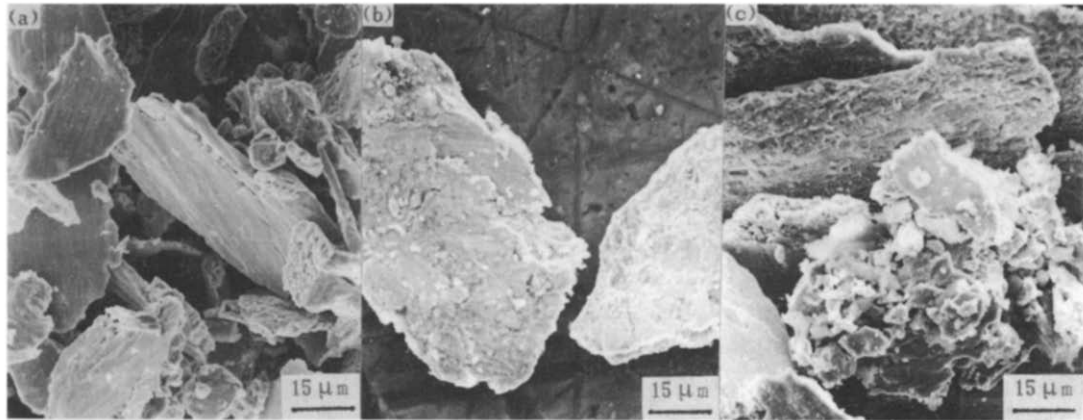


Fig. 8. Morphology of the worn debris of the pin specimens tempered for 2 h at 550 °C under various wear conditions: (a) $P=30$ N, $V=1.06$ m s⁻¹; (b) $P=70$ N, $V=1.47$ m s⁻¹; (c) $P=90$ N, $V=1.88$ m s⁻¹.

Scanning electron microscopy examinations show that the worn surface and debris morphology are in close relationship with the wear mechanism. Fig. 7 shows micrographs of the worn surface of specimens tempered for 2 h at 550 °C after dry sliding wear under different wear conditions. A mild worn surface formed at low load and sliding speed is shown in Fig. 7(a). The worn surface is comparatively smooth with a little ploughing and some tiny oxidative debris characterized by the mild oxidative wear. After the transition from mild oxidative wear to severe adhesive wear, the corresponding expression of the worn traces are roughened, grooves are deepened and some scale-like features appear on the worn surface, as shown in Figs. 7(b) and 7(c). The scale-like feature was considered in connection with higher contact pressure. Fig. 8 shows the micrographs of debris of pin specimens tempered for 2 h at 550 °C. From Fig. 8(a), very small amounts of tiny and thin metal flakes are produced together

with some tiny oxidative debris. As the normal load is increased, the plastic zones beneath the contacting asperities are grown. This leads to severe plastic flow. In general the transition from mild to severe wear is attributed to the interaction of the plastic zones beneath the contacting asperities. From Fig. 8, the three-dimensional size of the debris increases with test load and sliding speed during mild wear and severe adhesive wear. Fig. 8(c) shows the worn debris from severe wear, thick and big flakes appear, some flakes are rolled into a big spherical particle during the further wear process, because of repetitive deformation and intense plastic moulding.

4. Conclusions

- (1) Tempering leads to the decomposition of a large number of retained austenite in the laser quenched surface 10 μm thick and precipitation of chromium

carbides which nucleate at phase interfaces, sub-boundaries and within laths.

- (2) Cr_7C_3 carbide pinned by the dislocations lead to mild hardening effect when laser quenched layer was tempered for 2 h at 350 °C. With the further increase of temper temperature, chromium carbide coarsens and Cr_{23}C_6 gradually precipitate.
- (3) The change of the wear testing conditions causes the transition of wear mechanism from mild oxidation wear to severe adhesive wear with the feature of delamination.
- (4) For laser quenched 4Cr13 steel, tempering at 350 °C for 2 h leads to the appearance of transition wear effects only at higher loads or faster speeds.

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